A 28 GHz FR-4 Compatible Phased Array Antenna for 5G Mobile Phone Applications

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A 28 GHz FR-4 Compatible Phased Array Antenna for 5G Mobile Phone Applications

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***Abstract*— The design of a 28 GHz phased array antenna for future fifth generation (5G) mobile-phone applications has been presented in this paper. The proposed antenna can be implemented using low cost FR-4 substrates, while maintaining good performance in terms of gain and efficiency. This is achieved by employing a new air-filled slot-loop structure as the radiator. A prototype array consisting of ten radiator elements has been designed for concept validation. Both the radiation and total efficiencies of the antenna array are higher than -0.5 dB (90%) for the scanning range between 0º to 50º, while the gains are higher than 13 dB. In addition, the simulated and measured results show that the antenna has the S_{11} response less than -10 dB in the frequency range of 27 to 29 GHz.**

Keywords*—*5G; phased array antenna; FR-4, slot antenna.

I. INTRODUCTION

In the past decades, we have seen fast evolutions in the mobile communication systems from the first generation (1G) to the fourth generation (4G), where the newer generations always came with significant upgrades in their performance. The existing 4G systems can provide over 1 Gbps maximum data rates, which has made various attractive applications (such as wireless video calls, remote house monitoring and machine type communications) possible [1]. Furthermore, it is predicted that the commercial deployment of fifth-generation (5G) systems will be approximately in the early of 2020s [2]. In order to meet the increasing need for even higher data rates required in future applications (such as wireless broadband connections, massive machine type communications and highly reliable networks), the research activities on 5G mobile communication systems have started.

Compared with 4G systems, one of the major differences in 5G cellular systems is the shift to higher frequencies where is easier to obtain wider bandwidths. As illustrated in Fig. 1, the centimeter/millimeter wave bands could provide bandwidths several times broader than 3G and 4G frequency bands [3]. Therefore, the centimeter/millimeter wave bands can support the higher data rates required by applications in the future. In addition, there are different frequency band candidates that could be potentially used for 5G, and research activities can be found in all of these bands. However, moving to these centimeter/millimeter wave bands would bring new challenges in the designs of antennas for mobile phone devices [4].

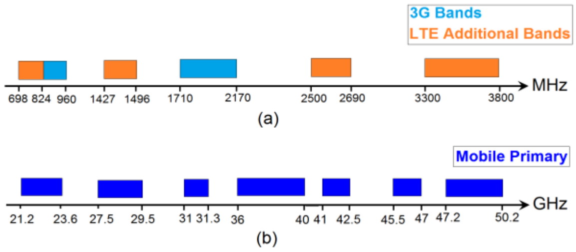

Fig. 1. (a) Frequency bands of 3G and 4G, (b) candidates Bands for 5G in 20-50 GHz (US).

According to the Friis transmission equation [5], by increasing the operation frequency, the path loss increases. So, in order to get the required gain overcoming attenuation effects, the smaller antennas arranged as an array are desired for millimeter applications.

One of the challenges in desigining antennas for 5G mobile phone devices is the implemetation of millimeter wave antenna arrays using the low-cost matirals such as FR-4. The FR-4 substrate features good and robust mechanical and electrical characteristics and hence has been widely used in custom electronic products. In addition, by using standard printed circuit board (PCB) processes, it is easier to achieve the strengint requirements on the interval distance between the antenna elements for the antenna array. However, the loss tangent of FR-4 is about 0.025. It is too lossy for millimeter wave antenna designs using taditional antenna structures such as printed patch antenna, where both gain and efficency of the antenna would be deteriorated.

This paper proposes a new design of air-filled slot-loop antenna array in a standard FR-4 PCB technology for millimeter-wave 5G mobile applications. The proposed design consists of ten slot-loop antenna elements which are located along the edge region of the mobile PCB. As the main substrate of the slot-loop elemets is the air with permittivity of 1 and loss tangent of 0, so they can achieve low loss and high antenna efficiency. The analysis and performance of the antenna are obtained by using CST software [6], and a prototype has been fabricated for experimental verification. The results show that the proposed phased array antenna has high efficiencies, acceptable gains and good beam steering characteristics at different scanning angles.

II. Configuration of Proposed 5G Antenna

The presented antenna configuration is shown in Fig. 2. The antenna is designed on an FR-4 substrate with thickness (h_{sub}) of 0.8 mm, permittivity (ε_r) of 4.3, and loss tangent (δ) of 0.025. The values of proposed design parameters are specified in Table I. The presented antenna array with ten elements of slot-loop resonator could be used in two sets of phased arrays in the top and bottom portion of the mobile phone PCB [7].

One of the important parameters of array designing which must be accommodate very carefully is set-out of the distance between the adjacent elements of an array. The decrement and increment in distance cause interference and distortion, not allowing the further assessment of received signals [8]. For beam forming array, the distance between antenna elements (d_1+W/2) is calculated close to λ/2.

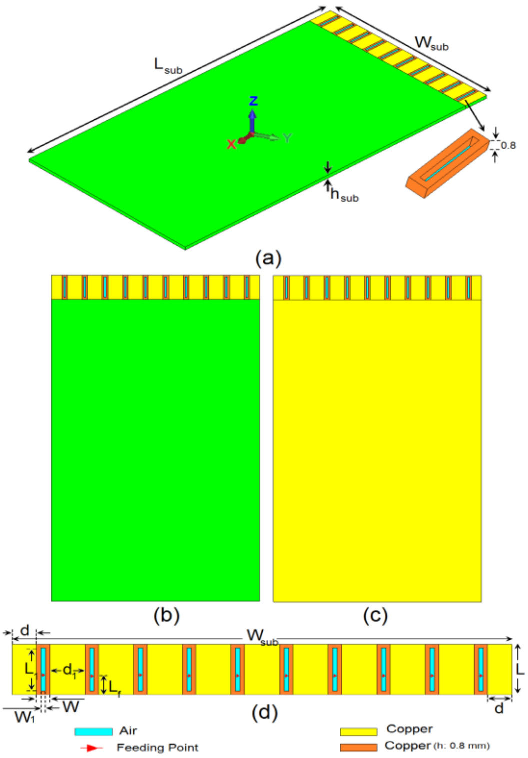

Fig. 2. Proposed 5G mobile-phone antenna configuration, (a) side view, (b) top layer, and (c) bottom layer, and (d) Geometry of the antenna array.

TABLE I. Final Dimensions of the 5G Antenna Parameters

Parameter	W_{sub}	L_{sub}	h_{sub}	W	L
Value (mm)	55	110	0.8	1.5	7
Parameter	W_1	L_1	d	d_1	L_f
Value (mm)	0.5	6	3.1	4.35	2.85

III. Results

A. *Slot-Loop Antenna*

Conventionally, the microstrip slot antenna (MSA) consists of a radiation element that is formed by cutting a narrow slot in a metal plate. The length of slot (*a*) is a half wavelength and the width (*b*) is a small fraction of a wavelength. This type of antenna is called the complementary dipole antenna [9].

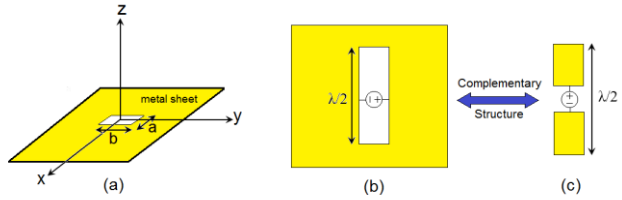

Fig. 3. (a) Side view of the conventional slot antenna configuration, (b) slot antenna (complementary dipole), (c) dipole antenna.

Configurations of the conventional slot antenna and its complementary structure are illustrated in Fig. 3. In this study, we started by designing a conventional slot antenna for 28 GHz. In order to improve the antenna performance and also eliminate the effect of high-loss FR-4 substrate, the reonator of the slot structure has been converted to the air-filled slot-loop structure with a thickness of h_{sub}. Configurations of the 28 GHz conventional-slot and slot-loop antennas are illustrated in Fig. 4. Figure 5 illustrates the simulated S_{11} characteristics of the conventional slot and proposed slot-loop antennas (descret-port feeding has been used to feed the antennas in the simulations.). It can be seen that both of the antennas have very similar respone.

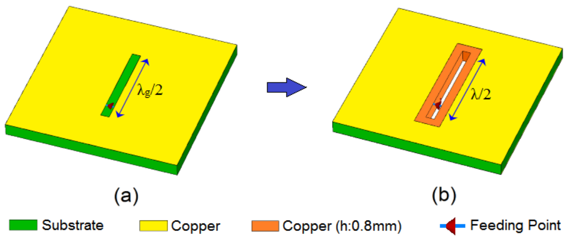

Fig. 4. Geometry of, (a) conventional slot antenna, and (b) proposed slot-loop antenna.

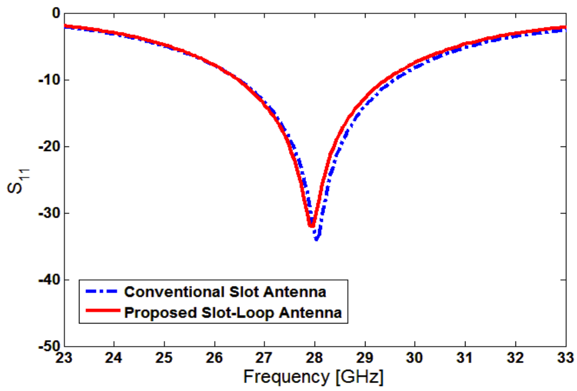

Fig. 5. Simulated S_{11} characteristics of the conventional slot antenna and proposed slot-loop antenna.

Figure 6 depicts the radiation and total efficiencies of the antenna shown in Fig. 4. As illustrated in Fig. 6, by using the proposed design (slot-loop antenna), the antenna efficiencies can be improved by about 0.5 dB in the band from 27 GHz to 29 GHz. And the radiation and total efficiencies are the same at the center frequency.

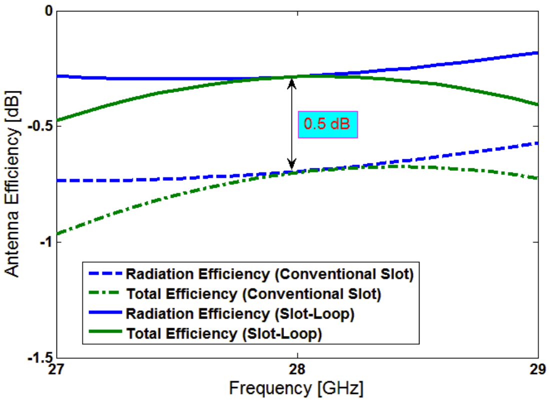

Fig. 6. Comparison of the simulated radiation and total efficiencies of the conventional and the proposed antennas shown in Fig. 4.

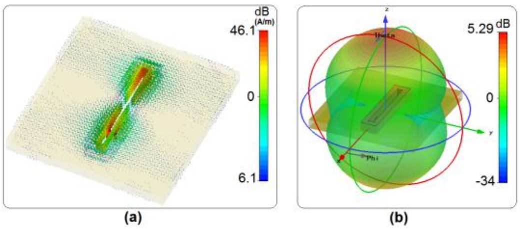

Fig. 7. Simulated (a) current distribution, and (b) 3D radiation pattern of the proposed slot-loop antenna element at 28 GHz.

Figure 7(a) shows the simulated current distributions for the slot-loop antennas at 28 GHz. As illustrated that most of the currents flow around the slot-loop resonator. In addition, the simulated 3D radiation pattern of the proposed single antenna element is illustrated in Fig. 7(b). It can be seen that the antenna has a good radiation behaviour with 5.29 dB realized gain at 28 GHz.

B. Beam Streeable Antenna for Mobile Phone Applications

The configuration of the proposed beam steerable antenna for mobile phone applications is shown in Fig. 2. The surface-current distribution for the antenna at 28 GHz is shown Fig. 8.

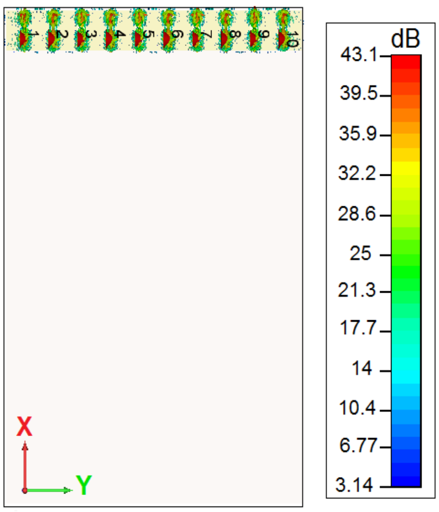

Fig. 8. Simulated current distribution at 28 GHz for the proposed antenna.

As illustrated, the current have concentrated on the edge regions of the mobile phone PCB and most of the current flows are distributed around of the slot-loop elements. Furthermore the effect of the full ground plane on the power of radiation is not significant. The simulated S-parameters of the proposed structure is illustrated in Fig. 9. It can be seen that the highest mutual-coupling characteristic between the elements are less than -18 dB which are sufficient for beam steering issue.

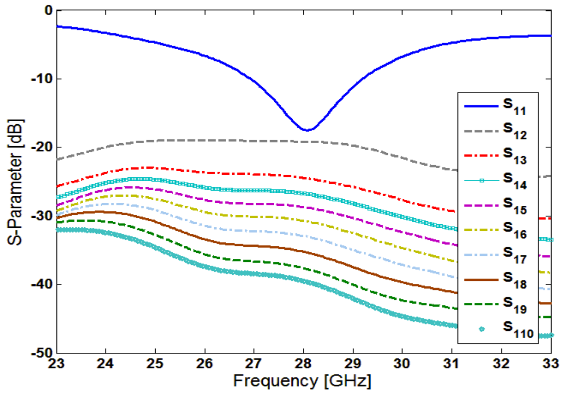

Fig. 9. Simulated S-parameters of the proposed 5G mobile-phone antenna.

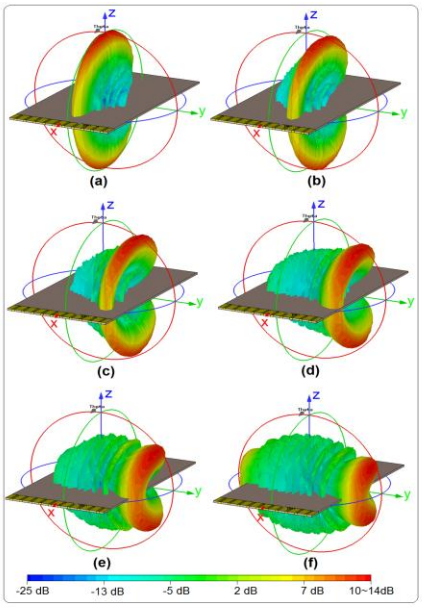

Fig. 10. Simulated 3D radiation patterns of each array for different scanning angles, (a) 0º, (b) 15º, (c) 30º, (d) 45º, (e) 60º, and (f) 70º.

The beam steering characteristic of antenna radiation patterns in different scanning angles at 28 GHz is shown in Fig. 10. As seen, the proposed antenna has a good beam steering property which is highly effective to cover the range of ±70º. The beam-steering characteristic of the proposed antenna for plus/minus (+/-) scaning angles are symertric. Figure 11 illustrates the simulated realized gains of the antenna. As seen, the antenna has a good gain levels in different scanning angles. For the scaning range of 0 to 50 degree the antenna has a consistant gain of about 13 dB.

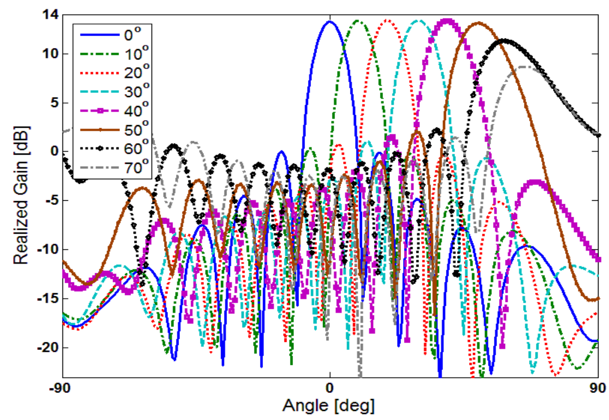

Fig. 11. Realized gain characteristic of the antenna for different scanning angles.

Simulated directivity, radiation efficiency and total efficiency characteristics of the proposed antenna for the scanning range of 0 to 60 degree are shown in Fig. 12. The antenna radiation and total efficiencies are more than -0.5 dB (90%) for the scanning range of 0º to 50º. It should be noted that the antenna has high efficiencies for different scanning angles. Furthermore, as can be seen, when the scaning angle of beam-steering characteristic is ≤ ±50º, the proposed antenna has more than 13dB directivity characteristic.

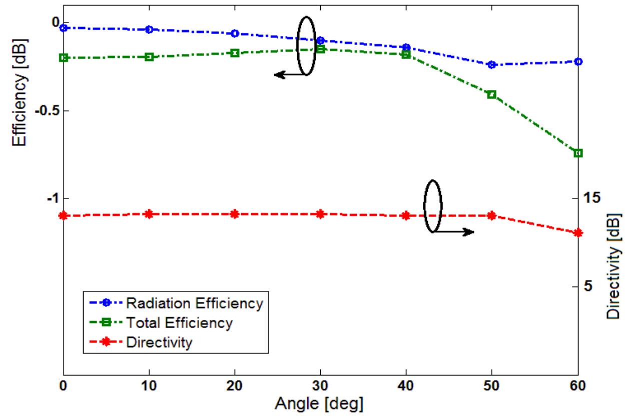

Fig. 12. Simulated directivity, radiation efficiency and total efficiency characteristics of the proposed antenna for different scanning angles.

The proposed design has been fabricated in a standard FR-4 PCB substrat. During the fabrication, ten slots for holding the elements were made on the PCB with an interval distance of λ/2. The slot-loop antenna elements were made seperately using a milling machine and inserted into the slots made on the PCB. The top and bottom view of the PCB are shown in Fig. 13. For measuring the antenna S-parameters, a coaxial cable was used for feeding the antenna elements (the inner conductor was extended from one side to the another side of the slot-loop resonator). Simulated and measured S-parameters (S_{11}) of the single element slot-loop antenna embedded in mobile-phone PCB are also shown in Fig. 13. As seen, the antenna has a good frequency response over the frequency range of 27 to 29 GHz and the experimental and simulated results are in good agreement.

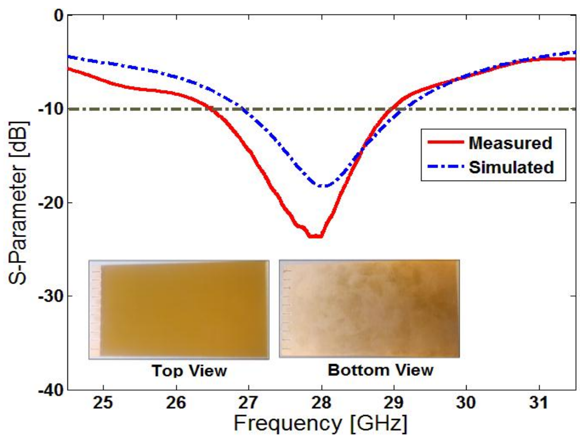

Fig. 13. Measured and simulated S-pameter (S_{11}) of the designed antenna.

IV. Conclusion

In this paper, a new air filled slot-loop phased array antenna aiming for 5G mobile communications is presented. The antenna is designed on a low-cost substrate (FR-4) to operate at 28 GHz. Ten elements of slot-loop antenna elements have been used for form a uniform linear array on the top region of the cellular handset PCB. The proposed antenna has good performance in terms of S-parameter, gain, efficiency, and beam steering characteristics. Experimental and simulated results are presented to validate the usefulness of the proposed phased array antenna for 5G applications.

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